AD-A282 037

June 16, 1994   Reprint

SOLAR OBSERVATIONS ON MAGNETO-CONVECTION

PE   61102F
PR   2311
TA   G3
WU   22

George W. Simon

Phillips Lab/GPSS
29 Randolph Road
Hanscom AFB, MA 01731-3010

DTIC
S ELECTE D
JUN 29 1994
F

PL-TR-94-2169

Proceedings of the Workshop on Gravitation, Magneto-Convection and Accretion at the Ringberg Castle, Tegernsee, FRG May 28-May 31, 1989

Approved for public release; distribution unlimited

Recent high-resolution observations of the solar photosphere
are described, as well as new techniques for image reconstruction
of ground-based atmospherically-disturbed images. These observations
already reveal various large-scale velocity structures and their
relation to magnetic fields and open up new possibilities for
magnetoconvection studies of the solar surface.

94-19782

94 6 28 126

14. SUBJECT TERMS			15. NUMBER OF PAGES
Solar image reconstruction, Magnetoconvection, Velocity fields, Magnetic fields, Granulation			6
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

MAX-PLANCK-INSTITUT FÜR PHYSIK UND ASTROPHYSIK
INSTITUT FÜR ASTROPHYSIK

PROCEEDINGS

of the Workshop on

GRAVITATION, MAGNETO-CONVECTION AND ACCRETION

at the Ringberg Castle, Tegernsee, FRG

May 28 – May 31, 1989

Bernd Schmidt, Hermann-Ulrich Schmidt, Hans-Christoph Thomas (eds.)
Max-Planck-Institut für Physik und Astrophysik
Institut für Astrophysik
Karl-Schwarzschild-Str. 1
D–8046 Garching, FRG

Solar Observations On Magneto-Convection

George W. Simon

Geophysics Laboratory (AFSC)
National Solar Observatory (Sacramento Peak)
Sunspot, NM 88349 USA

Introduction

I am very pleased that I was invited to participate in this celebration for Friedrich Meyer
and Jürgen Ehlers, and I congratulate them both for their long and still ongoing very
productive careers. This invitation continues a long-standing relationship between the
MPI für Astrophysik and the Sacramento Peak Observatory. When I came to Sac Peak as
a new Ph.D. in 1963, my first neighbor in the other half of our duplex house was Hermann
Schmidt, who was shortly later visited by Friedrich Meyer. So I have known them both
during my entire professional career. We have since worked and visited together on a
number of occasions, most recently in 1987 at Sac Peak.

Today I want to show you some examples of the very exciting new observations of
motions at the solar surface. They have opened a new era in the study of solar magneto-
convection. I regret very much that Prof. Biermann, who played such a key role in devel-
oping our ideas of stellar convection, is not here to enjoy these results. The observations
began with the Space Shuttle flight of Spacelab 2 in July 1985, and continue now with
high-quality ground-based data from Sac Peak, Pic du Midi, and La Palma. Almost all of
the work described below was done by Alan Title and his collaborators at the Lockheed
Palo Alto Research Laboratory, in some cases together with Larry November and me at
Sac Peak, Peter Brandt at the Kiepenheuer Institut, and Goran Scharmer of the Swedish
Solar Observatory (SSO). Alan has generously permitted me to present these observations
to you. Much of the material of this talk is shown as movies. In this written version I will
describe results from the movies and include some figures to illustrate the major points.

Background

First a little background: With the invention of the spectroheliograph by Hale (1) in
1892, photographs of chromospheric lines like CaK and Hα showed a network structure, as
though God had draped a sort of fish-net over the Sun. A typical mesh element or cell has a
diameter of 30 Mm. No one understood the source of the network until 1960, when Leighton
modified Hale's spectroheliograph so that one could obtain Doppler and Zeeman (i.e.,
velocity and magnetic) photographs. Immediately he and his collaborators (2,3) discovered
both the now-well-known five-minute oscillations and a large-scale convective flow pattern
which he named supergranulation. Supergranules lie within the network pattern, have the
same diameter, and it seemed likely then that these cellular flows push magnetic fields to

their boundaries where they congregate into the observed network pattern. Unfortunately supergranules were hard to observe, since they have primarily horizontal motions, and therefore cannot be studied at disc center with the Doppler effect. In 1965 at the MPI für Astrophysik I attempted to use granules as tracers of the large-scale flows, but managed to show only statistically that granules tend to move from the center to the boundaries of supergranules. The granules are distorted and shifted from their real positions by the Earth's atmosphere. Typically these distortions (noise) were 100× larger than the actual motions (signal) of the granules, so it appeared impractical to pursue this matter further. Therefore, after this paper was published (4) as part of Prof. Biermann's 60th birthday Festschrift, no work was done in this area for 20 yr. It seems very appropriate then, at this similar occasion 23 yr later, that I can at last show you what the granule motions really are.

Observations

Let us start with Spacelab 2 observations of the quiet Sun obtained with the Lockheed Solar Optical Universal Polarimeter (SOUP) (5). If one observes a time-series of such photographs in "slow" motion (say 10× real-time), one can scarcely discern any change at all between successive snapshots, since these data are essentially free of distortions; i.e., we now have a S/N ratio larger than unity (perhaps 300× bigger than in the earlier ground-based photos). If we now speed up such a movie to about 500× real-time, we do indeed see lots of granule motions, but at first glance they seem to be random, without a well-defined pattern. If one looks more carefully, however, many patterns emerge. For example, one sees many "exploding" granules, first noted by Rösch and Hugon (13) at Pic du Midi 30 yr ago. The new observations indicate that there are far more exploders then previously thought. Rösch had realized that exploders tend to repeat (or new ones emerge) at the same locations on the Sun. Now we see that these special loci are at or near the centers of the diverging flows which define supergranules and mesogranules. The mesogranules, an intermediate scale of convection (5–10 Mm in diameter) between granules and supergranules, were first seen by November (6) in 1981, but not well observed until these Spacelab 2 observations. Now it appears that they, rather than the better-known supergranules, may be the dominant scale of convection, other than granules, at the surface.

The method for seeing granule motions most easily is to compute the horizontal velocity vectors at each point in the field-of-view by measuring the shifts in positions of granules between successive photographs taken a few seconds apart. From the vector components (v_x and v_y), one then calculates the divergence:

$$\Delta = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} \tag{1}$$

from which it follows obviously that sources are the loci of maxima of Δ, and sinks minima. In Figure 1 are shown six examples of sources (on the left) and six sinks (on the right) with the divergence shown as contours. The Sun is covered by such objects. To gain further insight about these motions, we place a uniform distribution of test particles (corks) over

the field-of-view, and let each move according to the local velocity vector at its position. The corks move rapidly (in less than 1 hr) from source regions into the surrounding network, and then slowly (over many hours) congregate at sinks. This is illustrated in Figure 2 for a 65 × 65 arcsec area of the SOUP image. The significance of the cork motions will be discussed later.

In addition to sources and sinks we have also discovered vortex motions in the SOUP data. In this case we can compute the vertical component of the vorticity from the horizontal velocity vectors:

$$\zeta = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \tag{2}$$

Twelve such examples are shown in Figure 3, which contains six clockwise swirls on the left, and six counterclockwise on the right. Recently Brandt *et al.* (7) have described a particularly strong vortex which they observed at the SSO on La Palma. This vortex was associated with a strong sink, whereas many of the SOUP vortices have no sinks or sources in their immediate vicinity.

Up to now we have been discussing convection on the quiet Sun, away from magnetic regions. Let me turn now to magneto-convective phenomena. It seems to me that only the strong magnetic fields of sunspots are very effective in inhibiting convection at the solar surface. With SOUP we observed for the first time that normal photospheric convection is diverted by the sunspot, resulting in a strong radial outflow in the photosphere immediately adjacent to the penumbra-photosphere boundary. Granules observed in this roughly 5 arcsec wide annulus around the sunspot follow this pattern. Pores, which have field strengths only half as large as sunspots, say 1500 G compared to 3000 G, are barely able to withstand encroachment by photospheric granules, have continually changing shapes and sizes, and lifetimes of minutes or hours, compared to sunspots which may exist for many days. One also has a visual impression that granules are flowing into pores, just opposite the pattern around a sunspot. The presence of magnetic field in a region of pores does have another effect on the convection, because supergranules, which have diameters of 30 Mm in the quiet Sun, are only half that size, or even less, near pores and sunspots.

Unfortunately the SOUP instrument produced only white-light movies but no Doppler or Zeeman images. It was possible, however, to compare the SOUP data with a 9–hr series of magnetograms obtained at Big Bear Solar Observatory (BBSO) which ran from about 4 hr before, until 4 hr after, the SOUP observations. The results (8) are striking. To describe them, we again utilize the corks discussed earlier. The question we have in mind is whether we can use the corks as surrogates for magnetic flux elements; i.e., do the motions and positions of corks generated purely by granule motions have any relation to the behavior of the actual magnetic field? The answer is an unqualified *yes*, and comes from several correlations:

1) Both corks and field are excluded from mesogranular and supergranular source regions.

2) Both aggregate at network boundaries and sinks.

3) Wherever two opposing velocity flows meet, the field and corks pile up at this intersection, along the line perpendicular to both flow patterns.

10

These results are summarized in Figure 4, a superposition of a BBSO magnetogram (with opposite polarities shown as bright and dark) and corks after 12 hr of evolution from an initially uniform distribution. Four supergranules are labeled in Figure 4. The sunspot lies to the right of number 4 centered in the dark region where two corks are seen; a number of pores lie to the right of number 2, in the dark region centered on a line drawn from number 1 to 3. The correlation between cork and magnetic field locations is readily apparent, and is quite remarkable when one considers that the cork motions were all derived from only 27 min of granulation data, and the velocity field was then artificially extended 4 hr backwards and forwards in time to match the length of the BBSO movie. This is an important result, because it strongly suggests that the flow patterns at the solar surface change very little over a time-scale of 5–10 hr. Thus the underlying convection phenomena must have at least comparable lifetimes.

I close this section on observational results with some additional results obtained by the Lockheed group at Sac Peak (9) and La Palma (10). The Sac Peak and one of the La Palma time-series show sunspot groups in which several of the sunspots (consider them to be "foot points" of the magnet.c field) separate from others in the group, or move in a circle about the others. Such motions in earlier observations (Neidig *et al.* (14) at Sac Peak and Moore *et al.* (15) in Huntsville) are known to result in stress buildup in the magnetic configuration, leading to flares. In these new observations the same occurs. Simultaneous Hα data show small flares just in the areas of maximum footpoint motion. It may thus become possible to predict when and where flares will occur simply by measuring granule motions in active regions. One of the La Palma time-series also shows magnetic field reconnection, in which flux streaming outward from a sunspot meets opposite polarity flux in the surrounding region. The latter flux disappears as a result of the contact. Another phenomenon is the emergence of new flux within supergranules, which then moves quickly toward the nearest cell boundary. The final La Palma time-series is of a sunspot, obtained by Scharmer (11) last summer. In this excellent movie, which was processed by Shine at Lockheed, one has several visual impressions:

1) Dark features are moving radially outward.

2) Bright features are moving inward, bend down sharply at the umbra, and connect to bright umbral dots within the umbra.

3) Granules stream outward into the surrounding photosphere from the outer edge of the penumbra (as noted earlier with SOUP data).

Modeling

Nigel Weiss and I have begun simple modeling (12) of the radial and azimuthal velocities of sources, sinks, and vorticies. I will conclude my talk by describing some of our efforts to date. First consider axisymmetric radial flow from a source in the anelastic approximation. If we assume a gaussian velocity potential:

$$\phi(r) = \frac{1}{2} V R e^{-(r/R)^2}, \tag{3}$$

11

so that the radial velocity is given by:

$$v(r) = V(r/R)e^{-(r/R)^2},$$ (4)

then the divergence is:

$$\Delta(r) = \frac{1}{r}\frac{d}{dr}[rv(r)] = \frac{2V}{R}\{1 - (r/R)^2\}e^{-(r/R)^2}.$$ (5)

The functions $v(r)$ and $\Delta(r)$ have the shapes shown in Figure 5, from which V and R are obtained simply as $V = 2.332v_o$ and $R = 1.414r_o$. Note that the functions in equations 3, 4, and 5 are completely determined by the two parameters V (strength) and R (size) of the sources. (In Figure 5 we have set $V = R = 1$).

We use this model to fit a source seen in the vicinity of the La Palma vortex of Brandt et al. (7), and show the result in Figure 6. The observed divergence (shown as circles) and radial velocity (squares) are seen to agree well with our model (solid lines), even though the source is elongated and irregular in shape, not at all axisymmetric. Beyond about 1.5 arcsec from the source center the observational and model curves diverge; here the effects of neighboring sources and sinks distort the data (the model, of course, is for the idealized case of an isolated source).

In similar fashion we describe the azimuthal flow in a vortex by assuming a gaussian vorticity distribution:

$$\zeta(r) = \frac{1}{r}\frac{d}{dr}[rw(r)] = \frac{V}{R}e^{-(r/R)^2},$$ (6)

so that:

$$w(r) = \frac{VR}{2r}\left[1 - e^{-(r/R)^2}\right],$$ (7)

with a circulation:

$$\Gamma(r) = 2\pi rw(r) = \pi VR\left[1 - e^{-(r/R)^2}\right].$$ (8)

These functions are illustrated in Figure 7 (again plotted with $V = R = 1$), from which we obtain $V = 3.134v_o$ and $R = 0.8921r_o$. With these equations we fit the observed vortex, as can be seen in Figure 8. In this case the vorticity is shown as circles, the azimuthal velocity as squares, and the circulation as ×'s, each compared to a solid line representing the model. As in the previous example, the vortex is far from being isolated or axisymmetric; nevertheless, the fit is good out to a radius of 3.5 arcsec.

It is encouraging that such a simple model does such a creditable job of representing the observed flow patterns, and we plan to extend it in the near future to describe both "normal" and "exploding" granules.

Finally, I wish again to thank Hermann Schmidt for inviting me to this meeting, and offer my best wishes to Friedrich Meyer and Jürgen Ehlers that they will be able to continue their research for many more years.

References

[1] Hale, G. 1892, *Astr. & Astr.- Phys.* **11**, 407.

[2] Leighton, R., Noyes, R., and Simon, G. 1962, *Ap.J.*, **135**, 474.

[3] Simon, G. and Leighton, R. 1964, *Ap.J.* **140**, 1120.

[4] Simon, G. 1967, *Zs.Ap.* **65**, 345.

[5] Title, A., Tarbell, T., Simon, G. and the SOUP Team 1986, *Adv. Space Res.* **6**, 253.

[6] November, L., Toomre. J., Gebbie, K. and Simon, G. 1981, *Ap.J.* **245**, L123.

[7] Brandt, P., Scharmer, G., Ferguson, S., Shine, R., Tarbell, T. and Title, A. 1988, *Nature*, **335**, 238.

[8] Simon, G., Title, A., Topka, K., Tarbell, T., Shine, R., Ferguson, S., Zirin, H. and the SOUP Team 1988, *Ap.J.* **327**, 964.

[9] Title, A., Tarbell, T. and Topka, K. 1987, *Ap.J.* **317**, 892.

[10] Title, A. 1988, unpublished, private communication.

[11] Scharmer, G. and Shine, R. 1988, unpublished, private communication.

[12] Simon, G. and Weiss, N. 1980, *Ap.J.* **345**, (in press, 15 Oct).

[13] Rösch, J. and Hugon, M. 1959, *C.R. Acad. Sc. Paris* **249**, 625.

[14] Neidig, D., DeMastus, H. and Wiborg, P. 1978, *AFGL-TR-78-0194*.

[15] Moore, R., Hagyard, M. and Davis, J. 1987, *Solar Phys.* **113**, 347.